Development of a Traumatic Abdominal Injury Module for Estimation of Injury Probability During an International Space Station Mission

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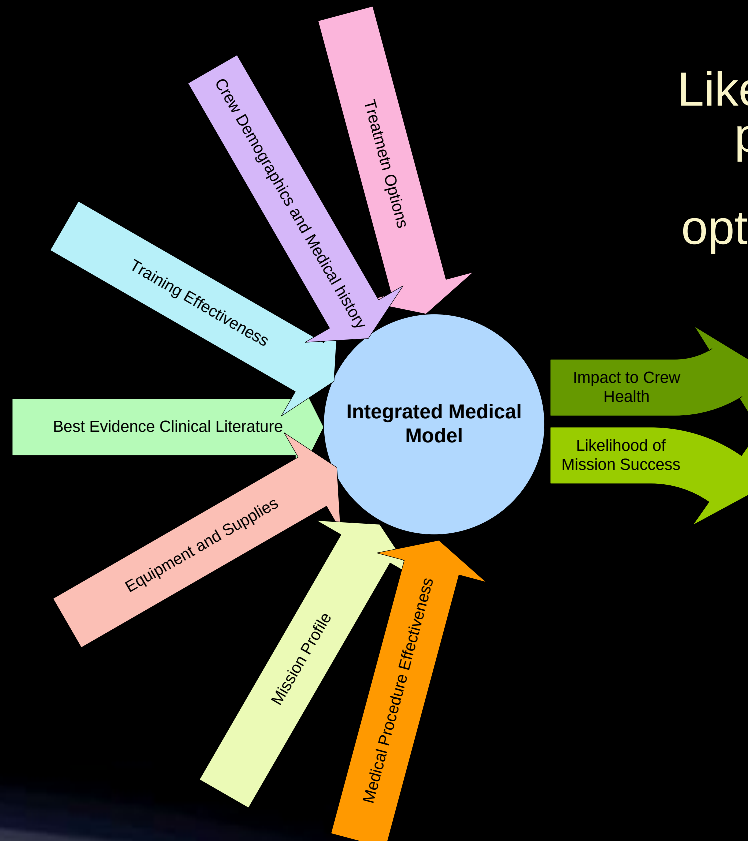
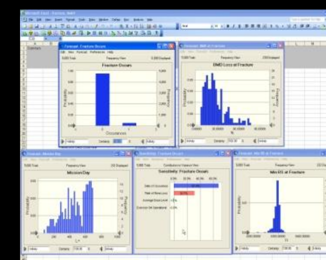
Integrated Medical Model (IMM)

Potential Medical Condition

Evaluate with IMM



Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.



- Probability and consequences of medical risks
- Integrate best evidence in a quantifiable assessment of risk
- Identify medical resources necessary to optimize health and mission success

Probabilistic Modeling of Rare Medical Events

- Event has not happened during a space mission
  - No incidence rate
  - Many unknowns
- Construct a computational model
  - Define the initiating event scenario and resulting injury
  - Determine available data and develop parameter distributions
  - Mathematically model the physiological response
  - Perform Verification and Validation
  - Relate the physiological response to probability of injury
  - Determine probability of occurrence
- Use probabilistic risk assessment methodology
  - Monte Carlo simulations
  - Estimate the most likely probability and confidence intervals

Initiating Event Scenario and Injury Definition

- An astronaut translating with equipment too large to see around accidently impacting another astronaut in the abdomen with attention focused elsewhere

- Traumatic abdominal injury defined as an injury with an Abbreviated Injury Scale (AIS) score of 3 or higher

AIS definitions for abdominal injuries

AIS	Injury Severity	Description
1	Minor	skin/muscle contusion (hematoma)
2	Moderate	spleen or liver contusion (< 50% surface area)
3	Serious	major kidney contusion
		spleen rupture
4	Severe	abdominal aorta: minor laceration
		kidney/liver rupture
5	Critical	kidney: total destruction of organ and vasculature
6	Maximum	hepatic avulsion

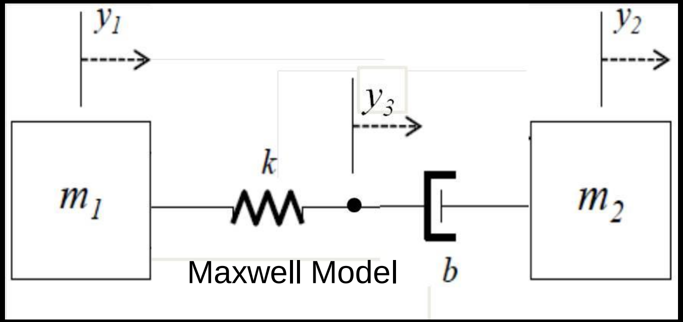
Schmitt K-U et al., *Trauma Biomechanics: Accidental Injury in Traffic and Sports*, Heidelberg: Springer, 2010.

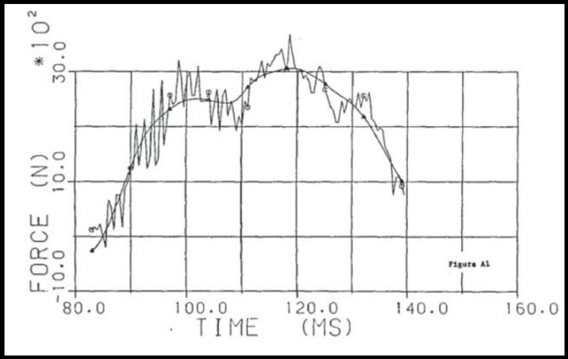
Parameter Distributions

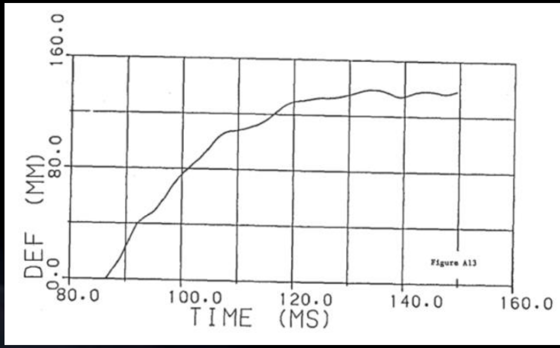
- Astronaut parameters
  - Astronaut mass
  - Abdominal depth
  - Translational velocity
- Mission parameters
  - ISS equipment masses
- Research data
  - Experimental impact response – impact force
  - Experimental impact response – normalized compression
  - Injury severity resulting from experimental impacts
- Spaceflight data
  - Impact rate

Biomechanical Model of the Abdomen

- A lumped mass-spring-damper model of the abdomen does not exist
- Force vs. time and deflection vs. time data from cadaver impact studies will be used to estimate the parameters of a simple mass-spring-damper model
- Voigt, Maxwell and Kelvin models are basic mechanical models that describe viscoelastic systems
- Evaluation of error between experimental data and model output will be used to determine the best model to use
- Complexity will be added to the simple models as needed



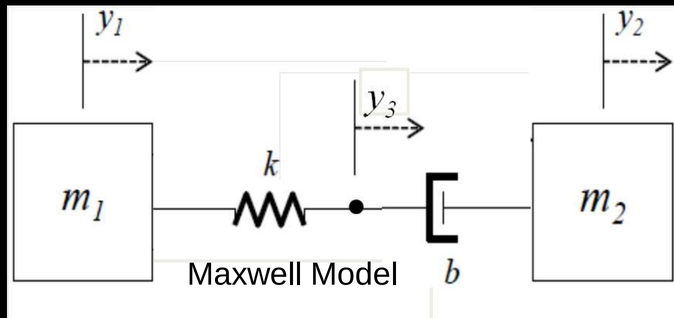




Example data: force vs. time and deflection vs. time

Cavanaugh et al., "Lower abdominal tolerance and response", SAE 861878,1986.

Biomechanical Model of the Abdomen



Symbol	Parameter	Units
k	Spring constant	N/m
b	Damping coefficient	Ns/m
m_1	Impactor mass	kg
m_2	Abdominal mass	kg
y_1	Displacement of impactor	m
y_2	Displacement of abdomen	m
y_3	Displacement between spring and damper	m
$\dot{y}_1$	Velocity of impactor	m/s
$\dot{y}_2$	Velocity of abdomen	m/s
$\dot{y}_3$	Velocity between spring and damper	m/s
$\ddot{y}_1$	Acceleration of impactor	m/s^2
$\ddot{y}_2$	Acceleration of abdomen	m/s^2
$\ddot{y}_3$	Acceleration between spring and damper	m/s^2
F	Impact force	N
d	System displacement	m
F_k	Force in spring	N
F_b	Force in damper	N
$\dot{d}$	Velocity of the system displacement	m
$\dot{x}_k$	Velocity of the spring	m/s
$\dot{x}_b$	Velocity of the damper	m/s

Equations of motion:

$$m_1\ddot{y}_1 + k\,(y_1 - y_3) = 0$$
$$m_2\ddot{y}_2 - b\,(\dot{y}_3 - \dot{y}_2) = 0$$
$$k(y_1 - y_3) - b(\dot{y}_3 - \dot{y}_2) = 0$$

Output:

$$F = k(y_1 - y_3)$$
$$d = y_1 - y_2$$
$$F = F_k = F_b$$
$$F_k = kx_k$$
$$F_b = b\dot{x}_b$$
$$d = x_k + x_b$$
$$\dot{d} = \dot{x}_k + \dot{x}_b$$
$$\dot{F} = k\dot{d} - \frac{k}{b}F$$

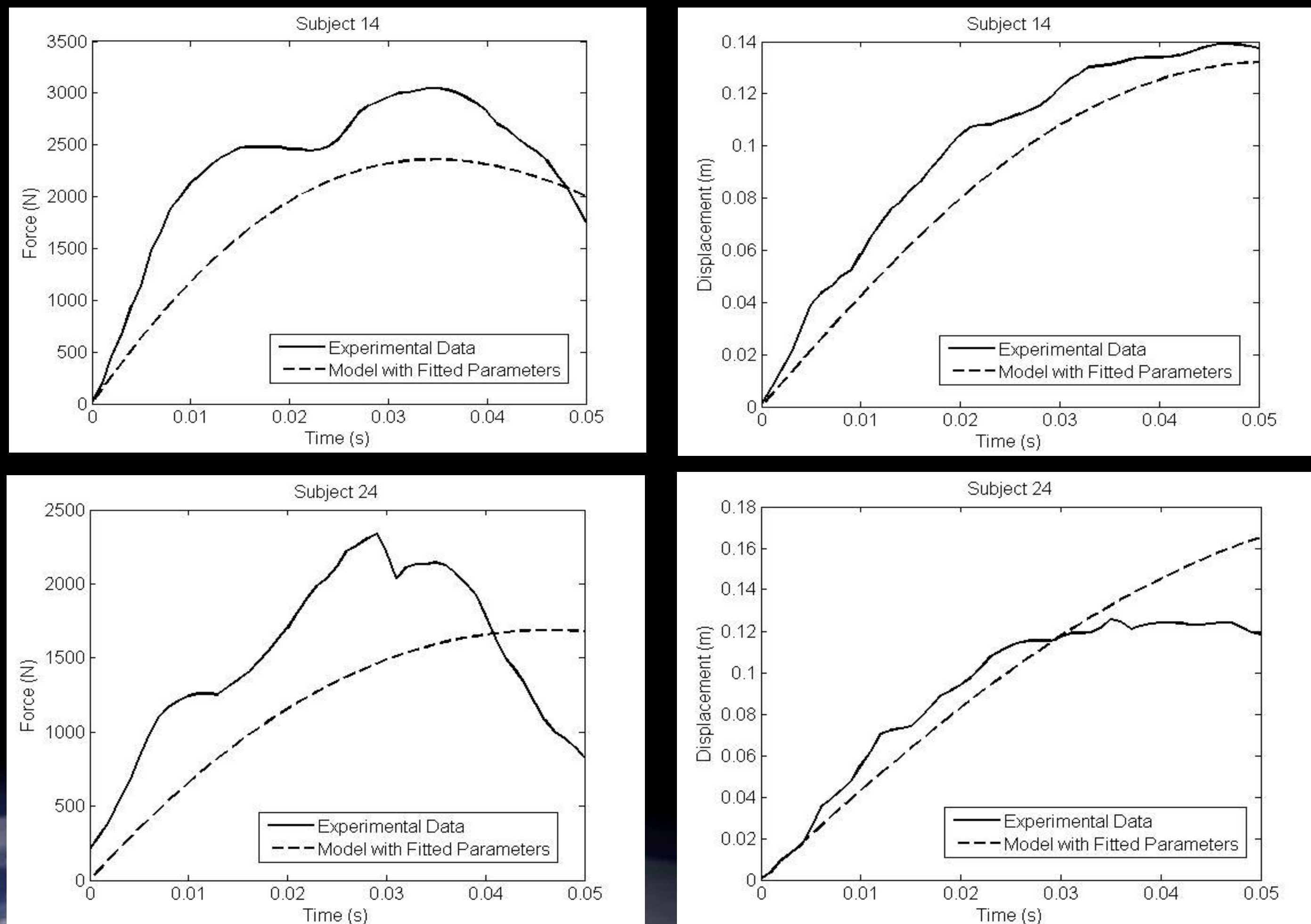
In matrix form:

$$Y = BX$$
$$Y = \dot{F}$$
$$B = \begin{bmatrix} k & -\frac{k}{b} \end{bmatrix}^T$$
$$X = \begin{bmatrix} \dot{d} & F \end{bmatrix}$$

To estimate parameters:

$$B = inv(X^T X)(X^T Y)$$

Example Results of Parameter Estimation



Subject 14, k = 31 kN/m, b = 1319 N/m/s
Subject 24, k = 17 kN/m, b = 900 N/m/s

Cavanaugh et al., "Lower abdominal tolerance and response", SAE 861878,1986.

Next Steps for Biomechanical Model

- Quantify error in Maxwell model parameter estimation
- Repeat using the Kelvin model in an effort to reduce parameter estimation error
- Verify model results against data used to estimate parameters
- Validate model against additional experimental impact data

Probability of Injury

- Translation between normalized compression and injury probability
  - Normalized compression and AIS score will be used from two impact studies
  - A 0 will be given to an AIS of 2 or lower, a 1 will be given to an AIS of 3 or higher
  - Matlab’s glmfit will be used to find the logistic regression coefficients (A & B) for the probability equation
  - The probability equation is:

$$P_{Injury}(NC) = \frac{1}{1 + e^{-(A+B*NC)}}$$

Miller, “Tolerance to Steering Wheel-Induced Lower Abdominal Injury.” *J. Trauma,* 31, 1332–9, 1991

Cavanaugh et al., "Lower abdominal tolerance and response”, SAE 861878,1986.

Probability of Impact

- Ideally, we would use a rate of the number of times an astronaut accidently impacts a piece of equipment with his or her abdomen during a mission
- However, this data does not exist
- Instead, we know there have been 6 minor trunk injuries in 26.4 years of flight and 0 traumatic abdominal injuries
- Since an impact must have occurred to cause the minor injuries, we use it as our maximum impact rate
- The impact rate (λ) is developed as an uniform distribution with 6/26.4 impacts/person*year as the maximum value and 0/26.4 impacts/person*year as the minimum value
- The impact probability equation is:

$$P_{Impact}(\lambda) = 1 - e^{-\lambda}$$

Scheuring et al, "Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts," *Aviat Space Environ Med*, 80(2), 117-24, 2009.

Next Steps for Abdominal Injury Module

- Complete biomechanical model and probability of injury equation
- Combine impact probability and injury probability within 100,000 Monte Carlo simulation trials performed to obtain most likely probability of traumatic abdominal injury
- Perform sensitivity analysis
- Complete verification and validation
- Incorporate the results into the parent Integrated Medical Model

Comparison of Chest and Abdominal Modules

- Similarities:
  - Initiating Event
  - ISS Equipment becoming the impactor
  - Translational velocity
  - Astronaut parameters
  - Probability of impact
  - Experimental impact data from same laboratory

- Differences:
  - Nature of the injury
    - Chest – both skeletal and soft tissue injuries, number of ribs broken correlated to injury severity, hemo- and pneumothorax and aorta laceration are the most severe injuries
    - Abdomen – only soft tissue injuries, rupture of spleen, liver, kidneys and major blood vessels are the most severe injuries
  - Biomechanical model used to estimate impact response
    - Chest – existing model in literature, incorporates viscoelastic elements of both skeleton and soft tissue
    - Abdomen – model under development using parameter estimation, only need to consider viscoelastic elements of soft tissue
  - Probability of injury
    - Chest – Higher correlation in the relationship between compression and injury levels, larger data set
    - Abdomen – Lower correlation, both injury and non-injury data points correspond to the same compression, smaller data set

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